

The present invention relates to an X-ray imaging method comprising forming a set of 2-dimensional X-ray images of an object to be examined, for example the coronary vascular system of a patient, by means of a scan rotation of an X-ray source around said object over a run length, said X-ray images being acquired at predetermined characteristic time moments in cardiac cycle of the object and a reconstruction of a 3-dimensional volume thereof. The invention further relates to a 3D-rotational X-ray apparatus for applying this method, the apparatus comprising a circular C-arm with a drive, the C-arm accommodating an X-ray source and an X-ray image pick-up device and being rotatable over an angle of substantially 180° around its center, triggering means for triggering the X-ray images at predetermined characteristic time moments in the cardiac cycle of the object and means for processing the images obtained to reconstruct a 3-dimensional volume of the object.

Such a method and apparatus are well known, e.g. from US-A-5,852,646. In said document a 3-dimensional volume of an object can be derived from a number of 2-dimensional computer tomograms by means of a CT-apparatus. The obtained 3-dimensional volume is related to the X-ray images; an association of corresponding projection images of this volume with the X-ray images results in a series of superposition images, which reproduces the two anatomic structures in geometrically correct association. In such a way information, inherent to CT-measuring methods, e.g. information about tumors, is combined with typically X-ray information, e.g. information about blood vessels.

In general, a similar set of X-ray images can be obtained by using an X-ray apparatus with a rotatable source around its isocenter. To enable such rotations conventional X-ray apparatus are equipped with a C-arm, the technical details of such a construction falling within the scope of general knowledge of a person skilled in the art of X-ray imaging. When a method as described in the opening paragraph is applied to a moving object, such as a beating heart or more specifically the coronary vascular system of a beating heart of a human or animal, filled with a contrast medium, it is often standard practice to use a C-arm rotation speed in the X-ray apparatus of about 30°/s (degrees per second) or a scan duration or run

length of about 6 s. During each run images are obtained for only certain angle areas. To cover the whole angle area of  $180^\circ$  several runs are necessary, the starting angle of each run relative to the cardiac cycle being adjusted by triggering the start of the run with a certain phase within the cardiac cycle. The images obtained can be used for a reconstruction of a 3-dimensional volume. During this process a movement of the heart contributes to artefacts in the reconstructed image. With a heart rate of 60 beats per minute and a framerate of for example 25 images per second during a scan movement over  $180^\circ$ , during each heart beat 25 images are obtained and with 5 images in each specific phase of the cardiac cycle, 6 times 5 images are obtained, or, in other words, during each scan 5 times 6 corresponding X-ray images of a quasi-stationary heart can be obtained, which can be used for reconstruction of a 3-dimensional volume. Problems of the known method are the necessity to correlate the different sub-runs in order to produce the  $180^\circ$  run as well as poor quality of the reconstructed image.

It is an object of the invention to provide a method where the above problems are solved. According to the invention, the method as described in the opening paragraph is characterized in that the run length of the scan rotation over substantially  $180^\circ$  is at least 15 s and preferably about 20 s. Contrary to the present tendency to increase the C-arm rotation speed, it has been found that the above method can be improved by a slower rotational scanning speed. With a run length of about 20 s, i.e. a C-arm rotation speed of substantially  $10^\circ/\text{s}$ , and with the above parameters, during each scan about 5 times 20 corresponding X-ray images of a quasi-stationary heart can be obtained. Thus, by reducing the speed of the rotation of the X-ray source around the object more X-ray images corresponding to the same phase in the cardiac cycle are acquired. This leads to reduced noise in the resulting reconstructed 3-dimensional volume.

A further embodiment of the X-ray imaging method according to the invention is characterized in that before reconstruction, images obtained at predetermined corresponding characteristic time moments in successive cardiac cycles are correlated with each other. This technical measure is based on the insight that each phase in the spectrum of cardiac activity in general represents the same spatial orientation and geometry of the heart muscle. Thus by correlating the X-ray images corresponding to the same phase of the cardiac activity, for example by known mathematical algorithms, one can further reduce noise in the final reconstruction of the 3-dimensional volume.

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Fig. 2 shows a cardiac cycle and preferred data acquisition times.

The imaging apparatus of fig. 1 serves to form two-dimensional X-ray images of an object to be examined, particularly a periodically moving object such as the heart and the coronary vascular system of the heart of a patient, from which two-dimensional images via reconstruction a 3-dimensional volume of the object can be obtained.

5 The imaging apparatus 1 includes a circular C-arm 10 which is mounted on a (only partly shown) stand 11. The C-arm can be rotated over an angle of for example  $180^\circ$  around its center in the direction of the double arrow 20 by means of a motor drive (not shown in the figure). The C-arm 10 accommodates an X-ray source 12 and an X-ray image pick-up device 13, which are aligned relative to each other in such a manner that an X-ray image can be formed of a volume to be examined around said center. A plurality of X-ray images can thus be formed. This plurality of X-ray images shows the volume to be examined from different angular positions (some of which are denoted by dashed lines) of the image-forming system 12, 13. The X-ray image pick-up device 13 may be an X-ray image intensifier whereto a television chain is connected whose output signals are digitized by an analogue-to-digital converter 14 and stored in a memory 15 so that the overall X-ray image series ( ... $D_{i-1}$ ,  $D_i$ ,  $D_{i+1}$ ,  $D_{i+2}$ , ...) will have been stored at the end of the examination. These X-ray images can be processed by known reconstruction methods in an image processing unit 16 to obtain the 3-dimensional volume to be examined. This volume or projections or cross sections thereof can be displayed on a monitor 18. The various components of the imaging apparatus 1 are controlled by means of a control unit 17.

Fig. 2 is a diagram showing the substantially periodic cardiac cycles H and preferred data acquisition time intervals during end diastole ED on an ECG scale. A heart is relatively stationary during the end diastole time interval.

According to the invention, the drive of the C-arm 10 is able or adjusted to perform a scan with a run length over  $180^\circ$  of at least 15 s and preferably about 20 s. With a heart rate of 60 beats per second and 25 images per second and a run length of about 20 s, i.e. a C-arm rotation speed of substantially  $10^\circ/\text{s}$ , during each scan about 5 times 20 corresponding non-moving X-ray images are obtained so that an improved reconstruction of the 3-dimensional volume will be possible.

30 The present invention is not restricted to the embodiment described with reference to the accompanying drawing, but also relates to modifications thereof as far as such modifications fall within the scope of the following claims. So, it is possible to reduce the number of measuring points in the end diastole time intervals or to reduce the number of corresponding measuring points in successive cardiac cycles. Although such a reduction

results in a reconstruction of less quality, the negative effect thereof may be compensated by combination of the reconstruction method with existing modelling techniques. Of course, also in the preferred embodiment with a large number of measuring points in each diastole time interval, reconstruction may be combined with modelling techniques.